ALPINIST 2.0

a unified simulation framework for feebly interacting particles in beam dump style experiments

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THE PLAN FOR THIS TALK

1. What are Heavy Neutral Leptons and what can they do for us?
2. An overview of ALPINIST framework
3. Using ALPINIST: Impact study of meson distributions on Sensitivity-Curves

WHAT ARE HEAVY NEUTRAL LEPTONS

One possible Dark Sector portal is the Dark Fermion

SM - - - - - - $hL\psi_D$ - - - - - - - **Dark Fermion**

➡**Heavy Neutral Lepton coupling to SM neutrinos with suppressed mixing $\sin\theta$**

Generally every I th HNL can couple to different lepton families α independently as $\theta_{\alpha I}$*

In small angle approximation mixing is commonly quantified by

$$U^2 = \sum_\alpha U_\alpha^2 = \sum_\alpha \sum_I U_{\alpha I}^2 = \sum_\alpha \sum_I |\theta_{\alpha I}|^2$$

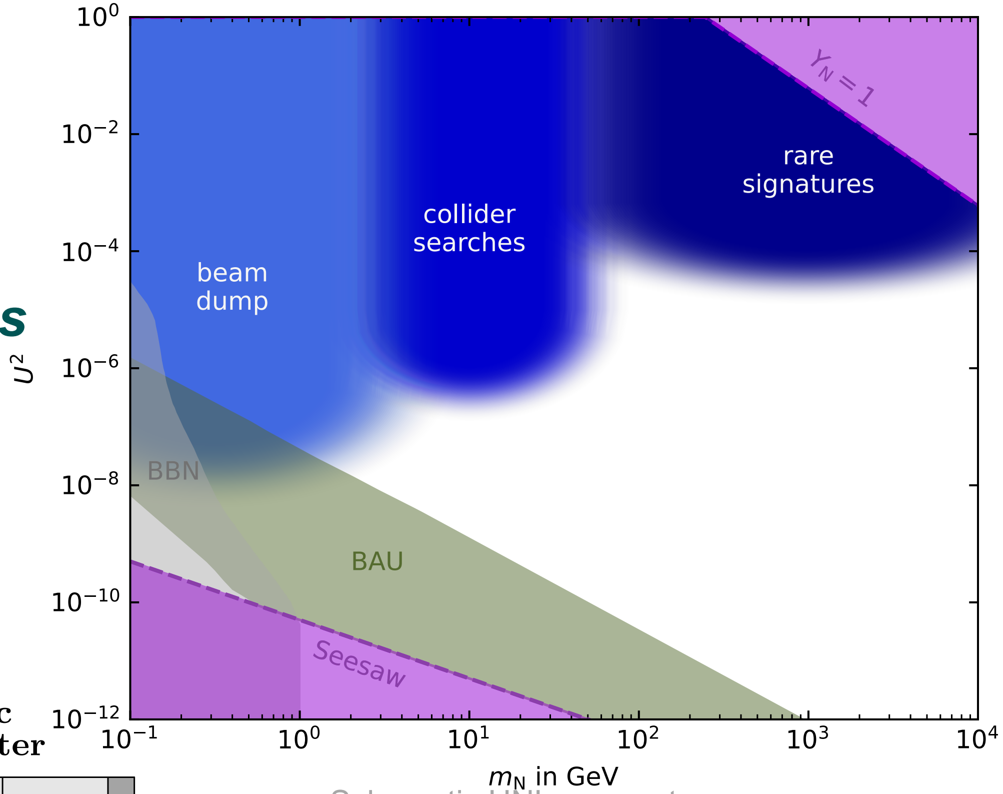
Resulting parameter space is arbitrarily complicated (3 HNLs→18 free param.s)

➡PBC **Benchmark Cases with only one HNL and one U_α active at a time**
(2 free param.s per BC)

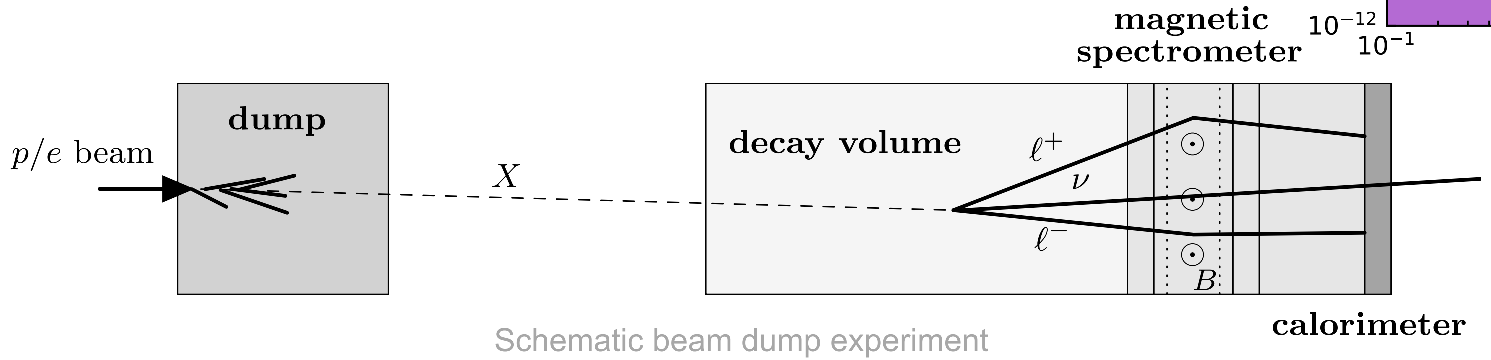
*See *Backup* for more info

HEAVY NEUTRAL LEPTON PHENOMENOLOGY HIGHLIGHTS

- **Heavy Neutral Leptons generate small neutrino masses in the *Seesaw Mechanism***
- **A mass degenerate pair of HNLs could lead to Baryon Asymmetry of the Universe through *resonant leptogenesis* with parameter space testable at beam dump experiments**



Schematic HNL parameter space



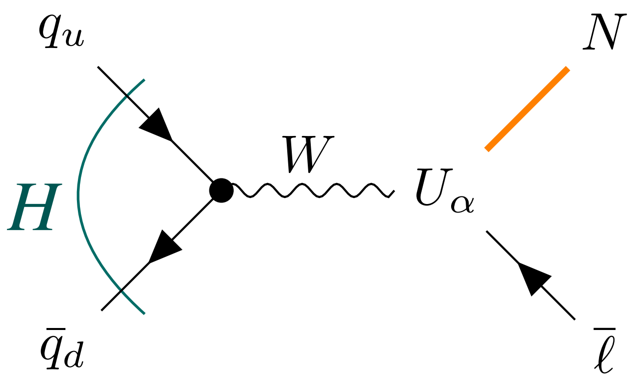
Schematic beam dump experiment

An additional ultra weakly coupled HNL can be added as a dark matter candidate

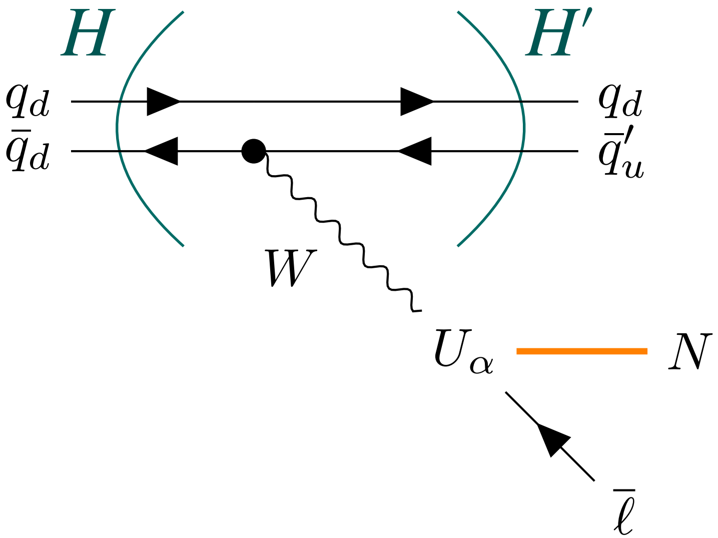
HNL PRODUCTION MECHANISMS

HNLs inherit interaction from SM neutrinos
➡ Weak interaction suppressed by U_α

Main production mechanism is the decay of secondary mesons:



2 body meson decays



3 body meson decays

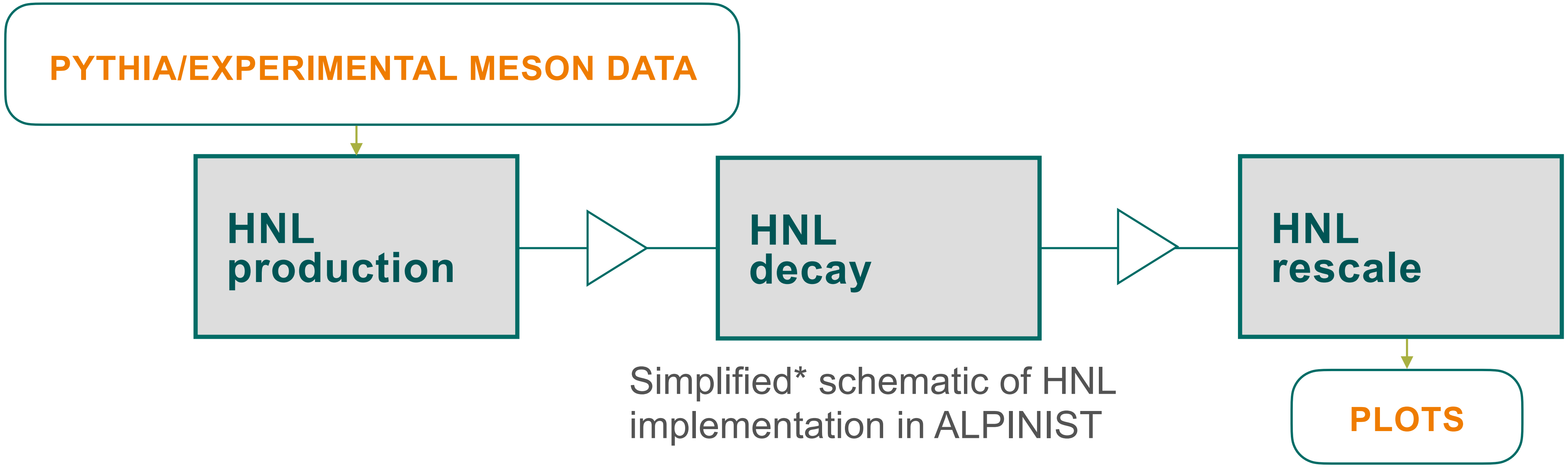
Most relevant are charmed (D) and beauty (B) mesons which are abundantly produced in proton-nucleus interactions at the beam dump.

For Majorana HNL charge conjugated process also possible

This is just an incomplete set of diagrams for illustration purposes

A QUICK WORD ON ALPINIST

- **Several simulation frameworks have been put forward to simulate Feebly Interacting Particles at beam dumps**
- **One of these is ALPINIST a simplified public BD-MC framework**
  - **Implementing experiment geometries (past, present and future)**
  - **Varying the underlying input distributions**
  - **Imposing analysis level cuts on signal**

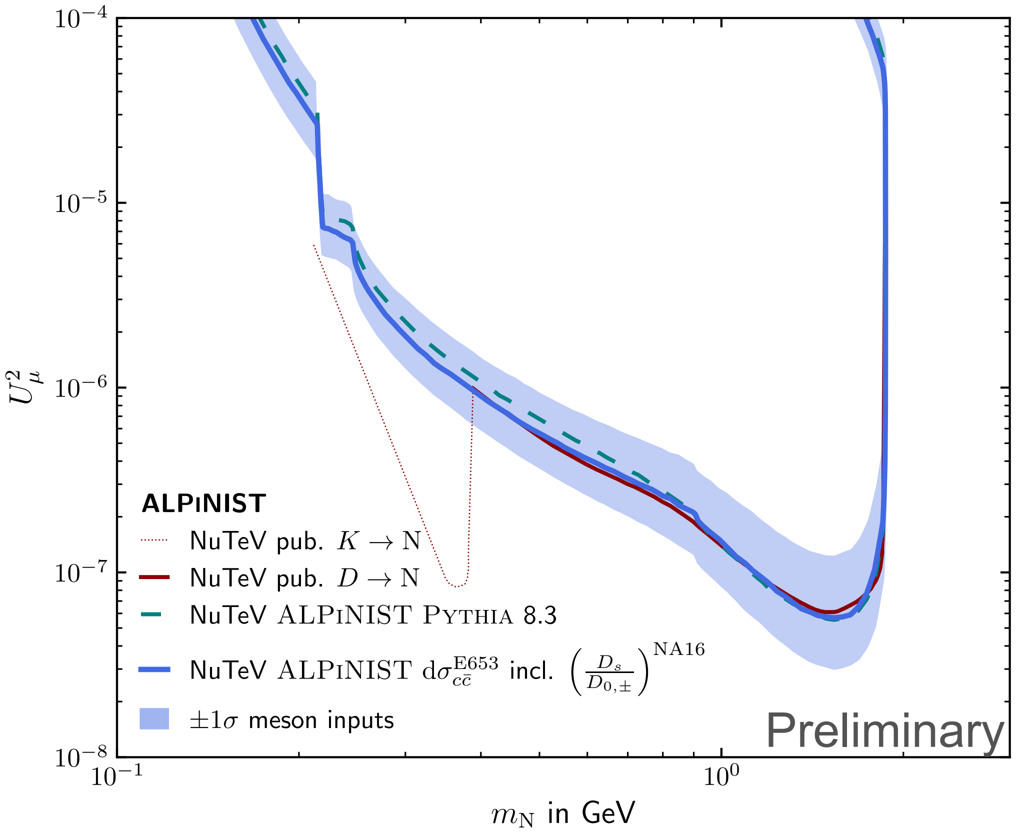


Simplified* schematic of HNL implementation in ALPINIST

*See *Backup* for more detail

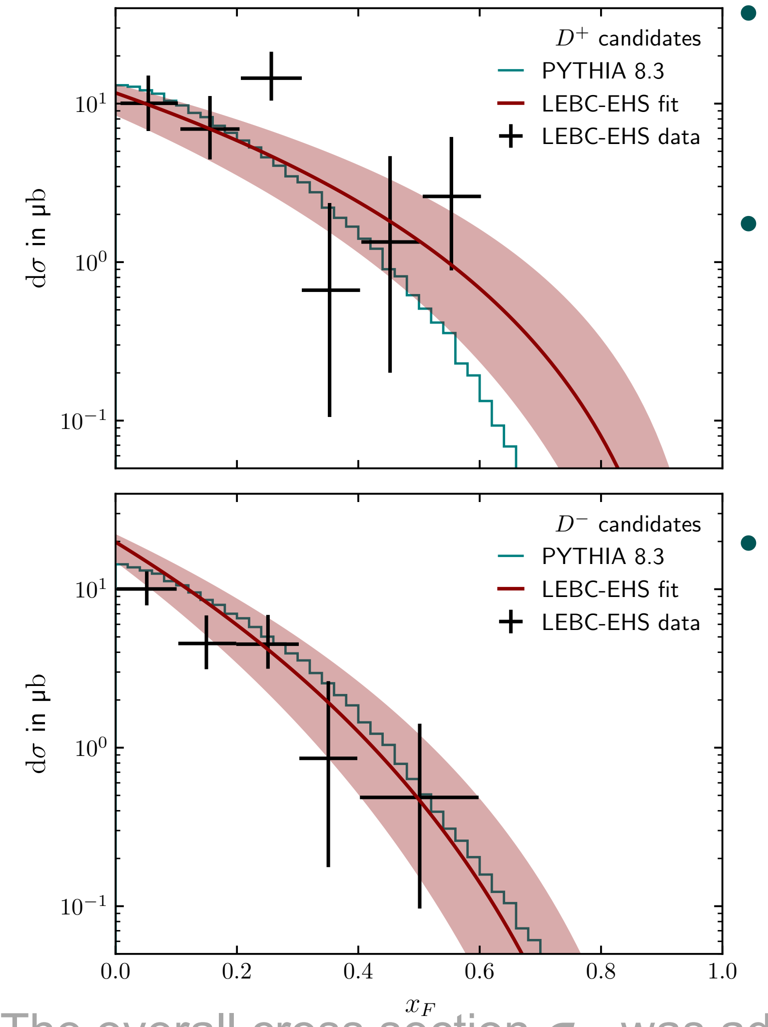
PAST EXPERIMENTS USING EMPIRICAL PARAMETERISATIONS

- **Past experiments looking for HNLs relied on empirical parameterisations of charmed mesons**
  $\mathrm{d}\sigma \propto (1 - x_F)^n \exp(-b p_T^2)$
  where $x_F = p_z^{\mathrm{cm}} {p_{z,\max}^{\mathrm{cm}}}^{-1}$
  - **usually all D mesons given the same kinematic distributions**
  - **added D_s mesons according to (measured) ratios**
- **Due to *leading particle* (beam remnant) effects these distributions are different for each $D, \bar{D}$, and D_s**
  - **accounted for in modern generators (like PYTHIA8.3)**

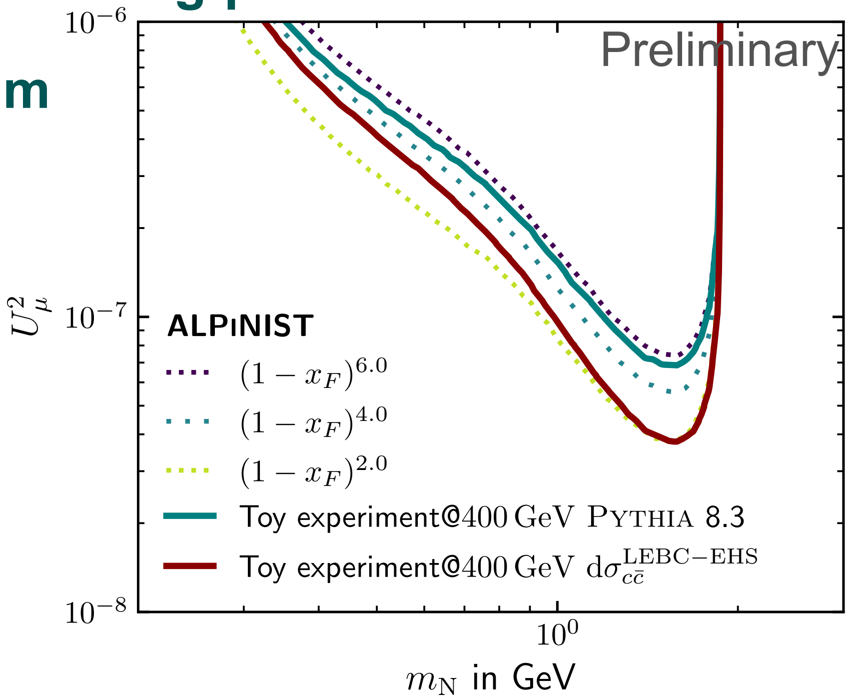


DPG Spring Meeting 2024

PLANNING FUTURE EXPERIMENTS USING PYTHIA



- **Pythia mostly in line with data showing the observed asymmetries of charmed/anti-charmed meson spectra in πNucleus collisions**
- ***LEBC-EHS* (NA27) remains only experiment to measure pNucleus interactions separating different D s at 400 GeV or comparable energies**
  - **Observed opposite of leading particle effect for $D^{\pm}$**
- **Reported Data differs from Pythia distributions**
  - **significant impact on forward experiments looking for HNLs**



The overall cross section $\sigma_{c\bar{c}}$ was adjusted

→ focus on kinematics (see *backup*)

CONCLUSION AND OUTLOOK

1. HNLs were implemented in the ALPINIST simulation framework
   - This implementation was verified to reproduce past searches for Heavy Neutral Leptons
   - The impact of different mesons distributions on the HNL parameter reach of forward experiments was studied systematically
2. Meson distributions determine the kinematics of resulting HNL
   - Very important role in the analysis of beam dump data taken at the NA62 experiment

1. The DsTau (NA65) experiment measures D_s decays in nuclear emulsions
   - hopefully releasing the tension with theory and bring down experimental uncertainty for charmed mesons production in $p\text{Nucleus}$ interactions
2. Beauty meson spectra have yet to be measured in this regime
3. The presented update to ALPINIST and these results regarding meson distributions will be made public in the very near future

BACKUP SLIDES

HEAVY NEUTRAL LEPTONS COUPLING TO THE STANDARD MODEL

Before electroweak symmetry breaking (EWSB) the Seesaw Lagrangian is written as

$$\mathscr{L}_{\text{seesaw}} = \mathscr{L}_{\text{SM}} + \frac{i}{2}\nu^{\dagger}_{\text{R}I}\bar{\sigma}^{\mu}\partial_{\mu}\nu_{\text{R}I} - \overbrace{\left(F_{\alpha I}\right)^{*}\left(L_{\alpha}\cdot\tilde{H}\right)^{\dagger}\nu_{\text{R}I}}^{\mathscr{L}_D} - \overbrace{\frac{M_I}{2}\nu^{T}_{\text{R}I}\nu_{\text{R}I}}^{\mathscr{L}_M} + h.c.$$

which after EWSB becomes

$$\mathscr{L}_D = -\left(F^{\nu}_{\alpha I}\right)^{*}\frac{v}{\sqrt{2}}\nu^{\dagger}_{L\alpha}\nu_{\text{R}I} + h.c. \Leftrightarrow (m_D)_{\alpha I} = \frac{v}{\sqrt{2}}\left(F_{\alpha I}\right)^{*}$$

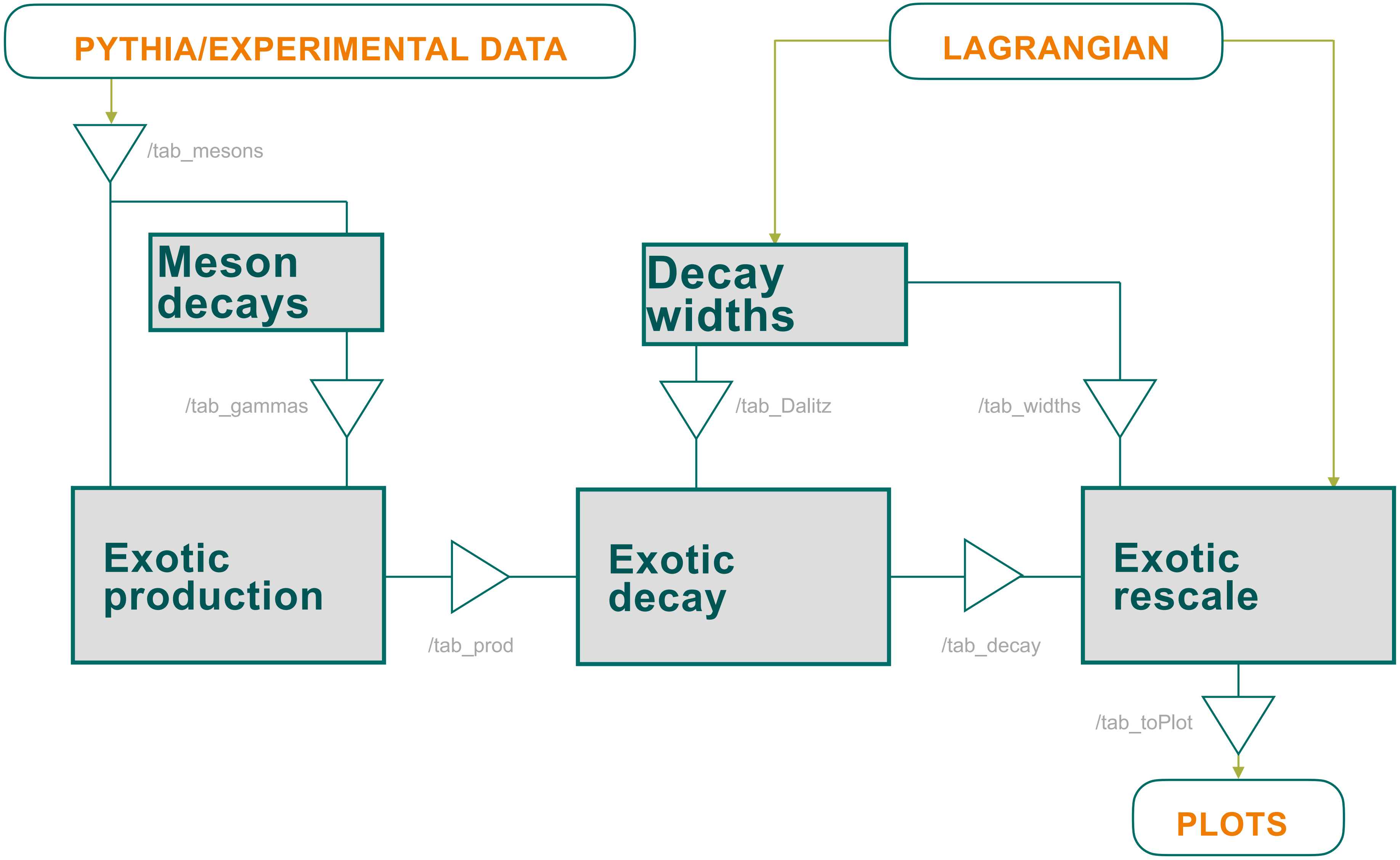
Diagonalising the mass terms gives rise to HNLs with masses $m_{\text{N}} \simeq M_R$ and light Majorana neutrinos with masses m_i

$$U^{\dagger}_{\text{PMNS}}\text{diag}(m_1, m_2, m_3)U_{\text{PMNS}} = -m_D M_R^{-1} m_D^T + \mathcal{O}\left((m_D M_R^{-1})^2\right)$$

Where we find the seesaw-equation $m_{\alpha\beta} = -\sum_I \theta_{\alpha I}\theta_{\beta I} m_{\text{N}I}$ on the with $\theta_{\alpha I} \equiv \dfrac{F_{\alpha I} v}{M_I}$.

We typically write $U^2_{\alpha} = \sum_I |\theta_{\alpha I}|^2$

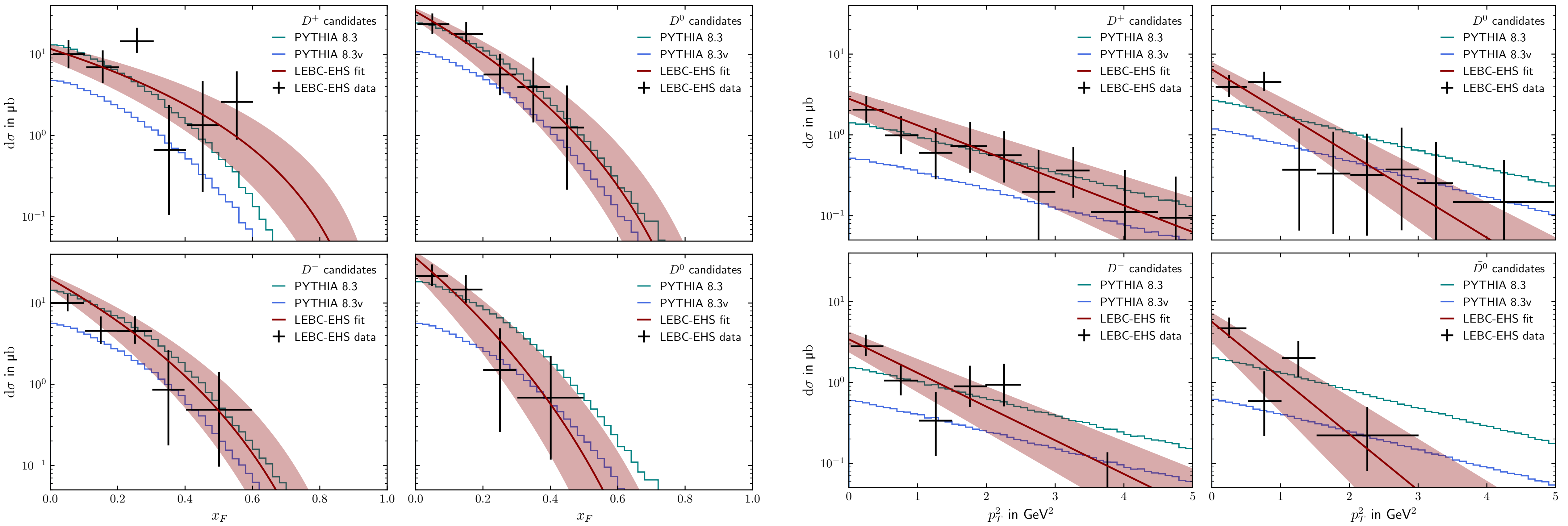
ALPINIST LAYOUT



CHARMED MESON KINEMATICS

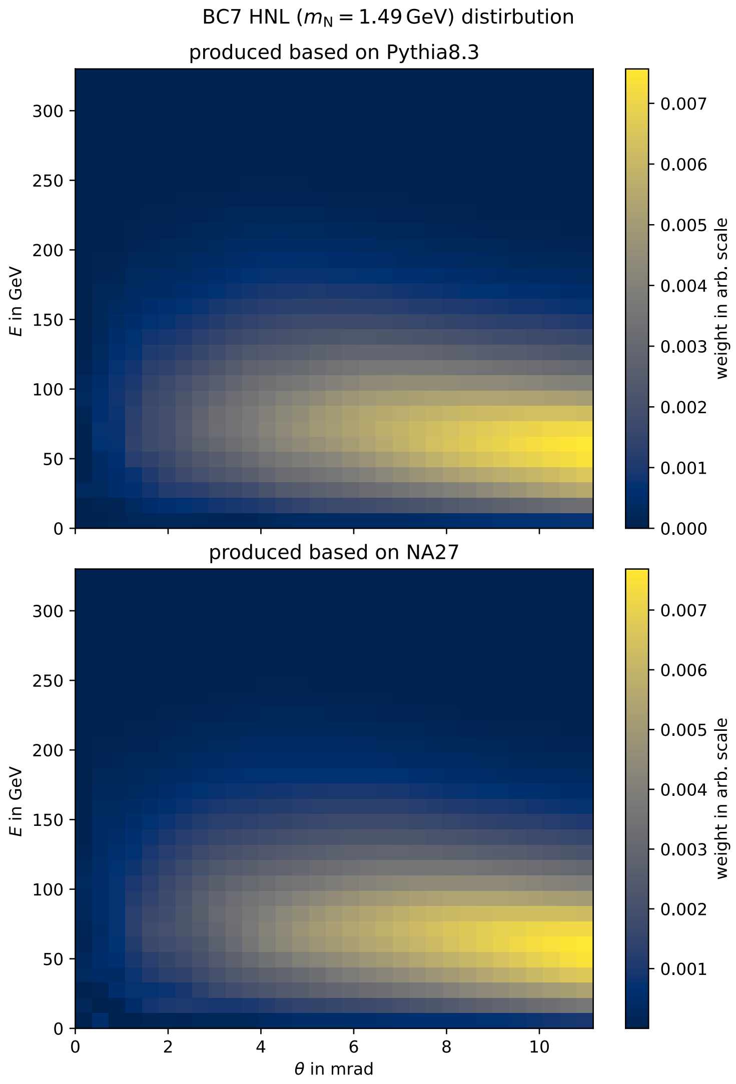
PYTHIA COMPARISON TO LEBC-EHS KINEMATIC CHARMED MESON DISTRIBUTIONS

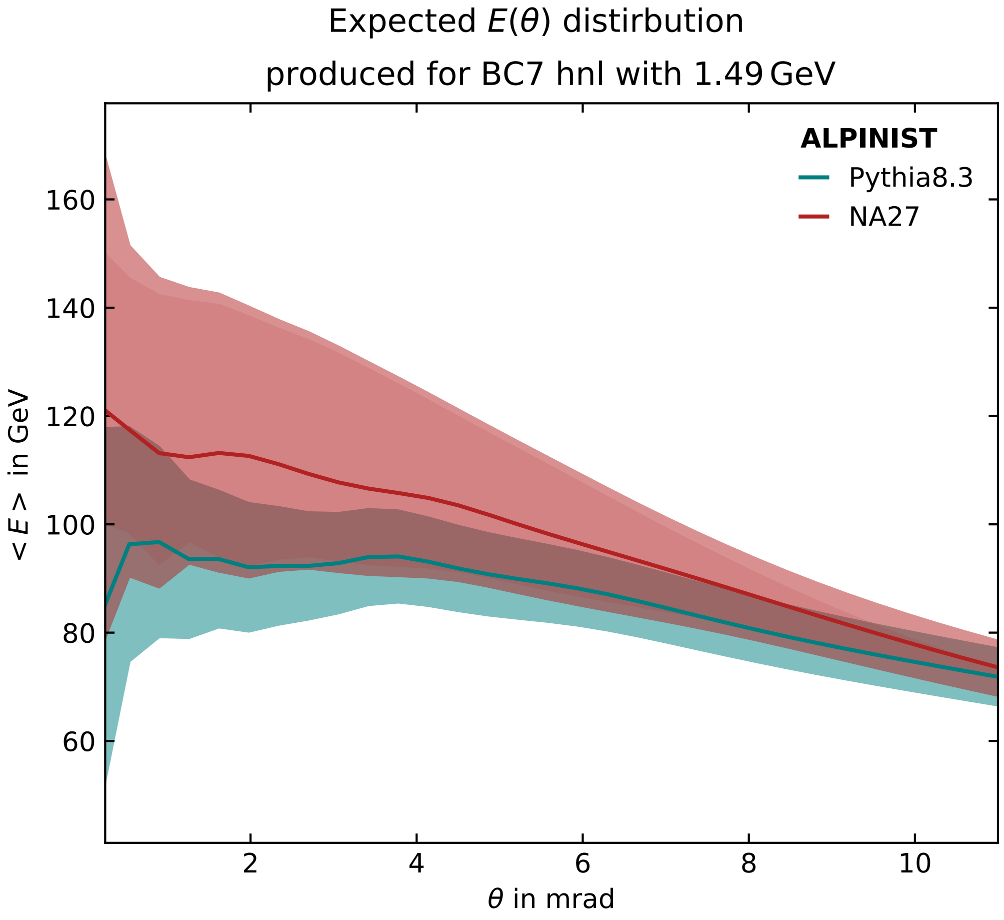
x_F $\qquad$ p_T^2 in GeV^2



v here refers to using the estimated cross section for $\sigma_{c\bar{c}}$ as the curve normalisation rather than the measured values

PYTHIA COMPARISON TO NA27
RESULTING HNL DISTRIBUTIONS





DIFFERENT INPUT ASSUMPTIONS
$c\bar{c}$ DIFFERENTIAL CROSS SECTION

- **$c\bar{c}$ very important for HNL search with NA62BD as production mainly in D-meson decays**
- **Especially forward region is not well constrained which has implications on HNL momentum distributions and consequently detector acceptance**
- **SHiP-charm *project* aims at measuring $c\bar{c}$ differential cross section and already ran a *pilot measurement* to validate their cascade interaction model**
- **Another experiment currently investigating distribution of charmed mesons is the *NA65 collaboration***

Primary and Secondary interactions MC vs data at the *SHiP-charm experiment*

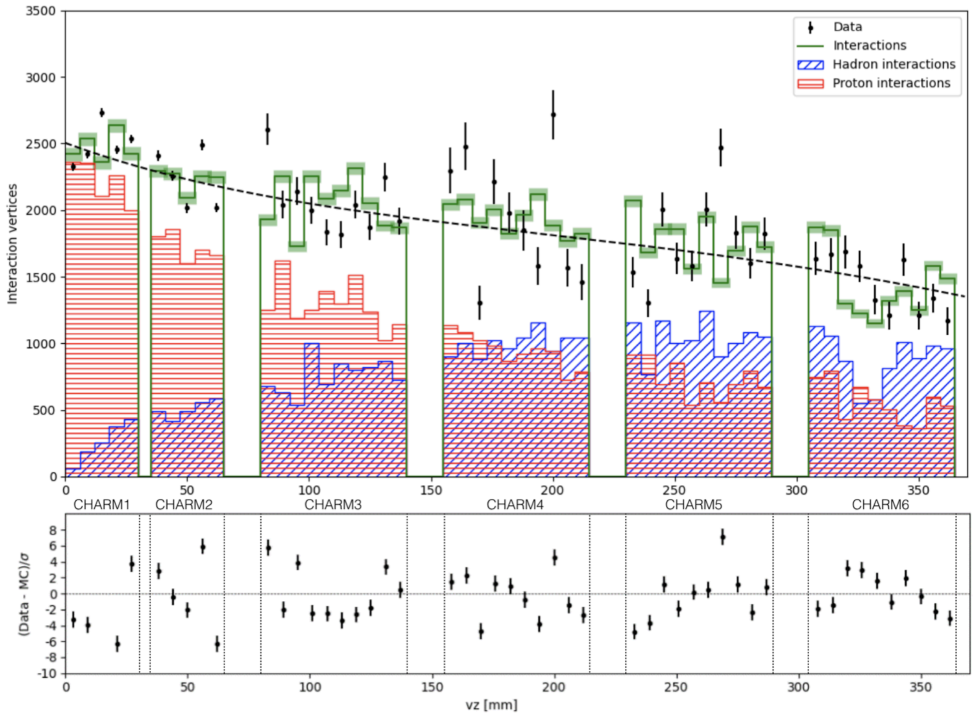


Figure 17: Position distribution of interaction vertices along the beam direction for data and Monte Carlo, merging results from the different configuration. Primary-proton and hadron-reinteraction components are shown in red and blue, respectively. Dashed line represents the fit to data points.

ABOUT INTERACTION OF MESONS WITH TARGET MATERIAL

Typical interaction length in copper is $\lambda_{\mathrm{Cu}} = 153.2\,\mathrm{mm}$

The most long lived charmed meson is $D^{\pm}$ with $c\tau_{D^{\pm}} = 309.8\,\mu\mathrm{m}$

➡It is safe to assume that mesons will very likely decay before they interact in copper.

DECAY FINAL STATES

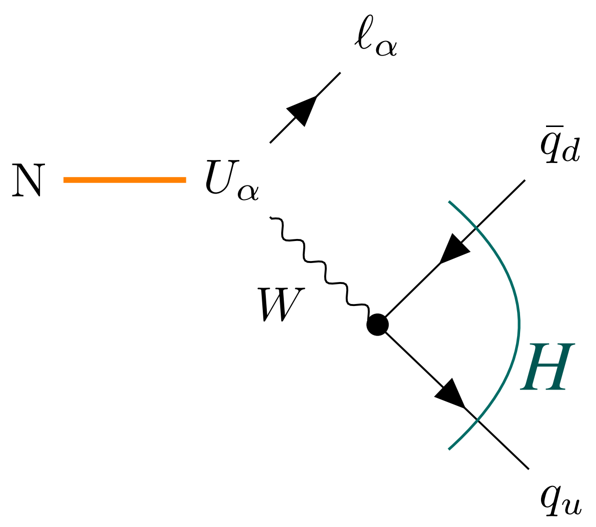
TWO BODY FINAL STATES

THE ℓH DECAY DEPENDING ON ACTIVE COUPLING

Dominant useful channels in relevant mass regime are

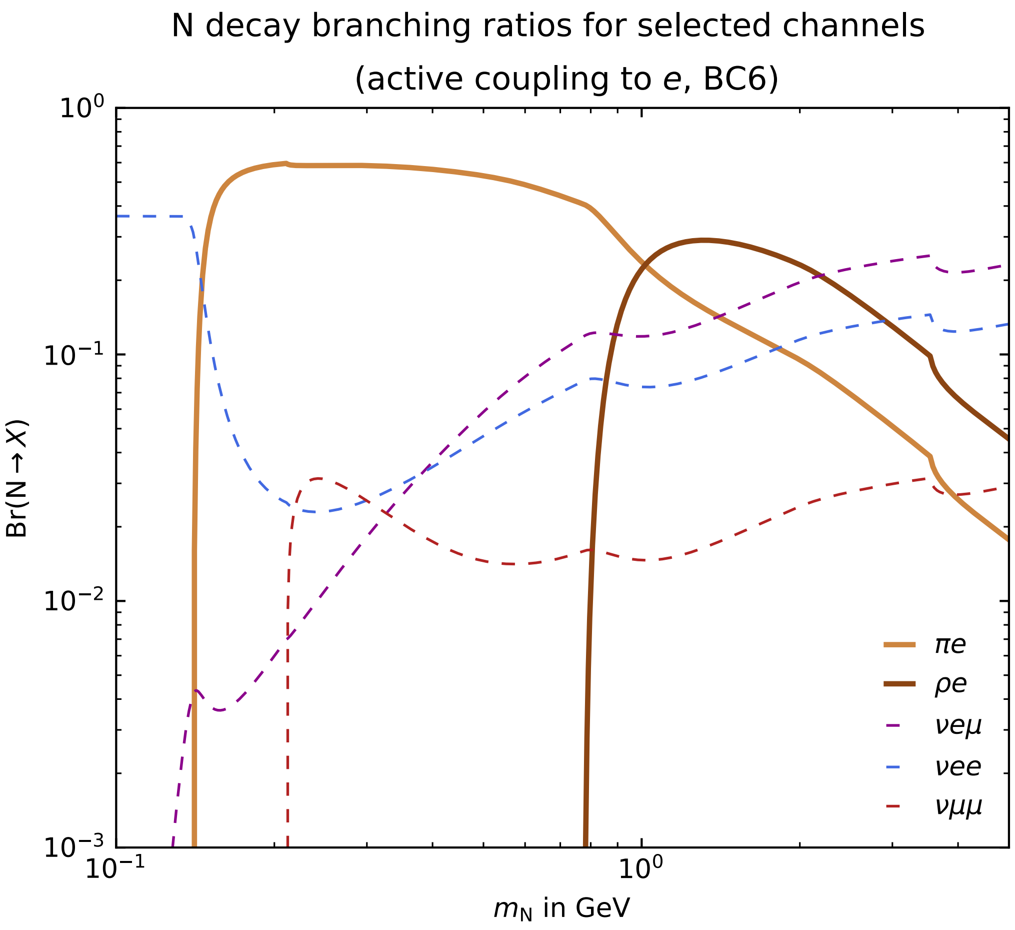
- $\mathrm{N} \rightarrow \ell\pi$
- $\mathrm{N} \rightarrow \ell(\rho \rightarrow \pi(\pi^0 \rightarrow \gamma\gamma))$

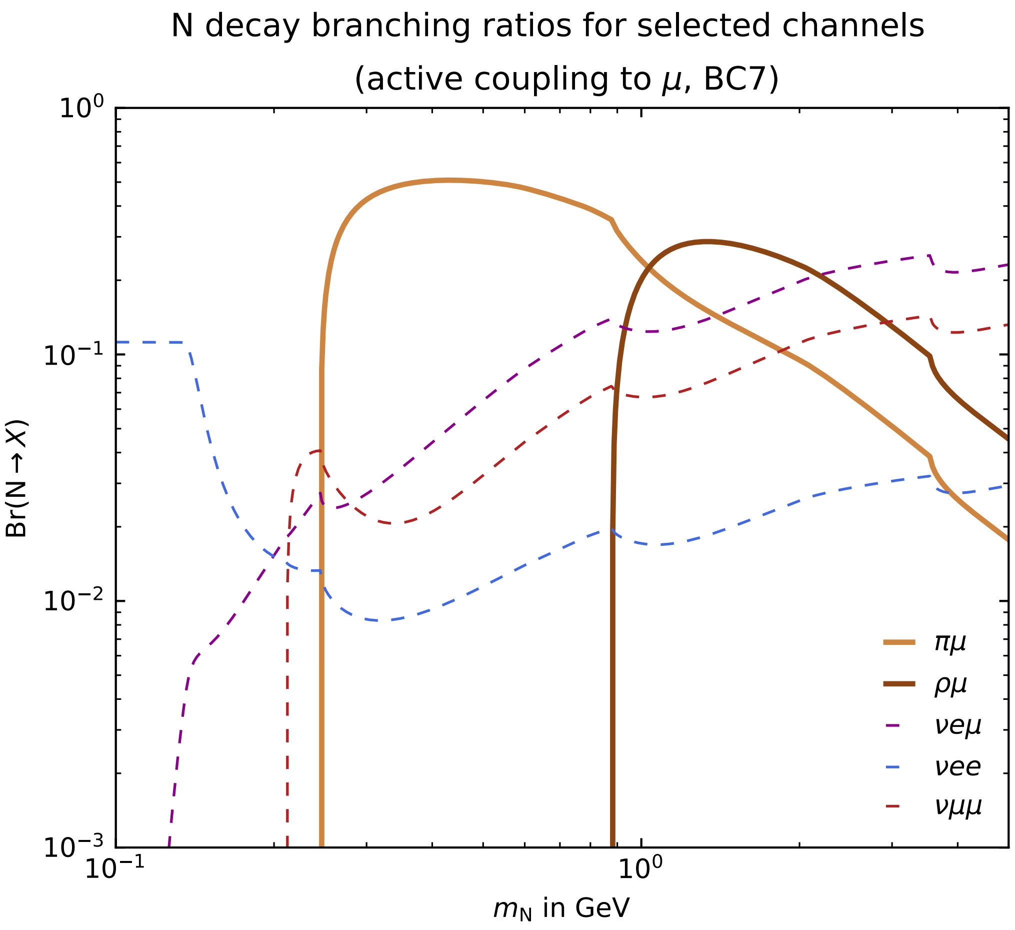
These can be fully reconstructed



For Majorana HNL charge conjugated process is also possible

TWO BODY FINAL STATES
THE ℓH DECAYS





THREE BODY FINAL STATES

THE $\nu\ell\ell$ DECAY DEPENDING ON ACTIVE COUPLING

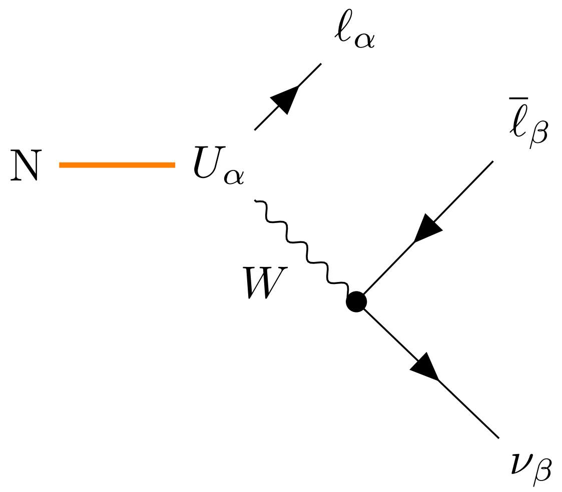
We get only Z channel if the HNL coupling does not match $\ell\bar{\ell}$ which turns out to be subleading but not negligible

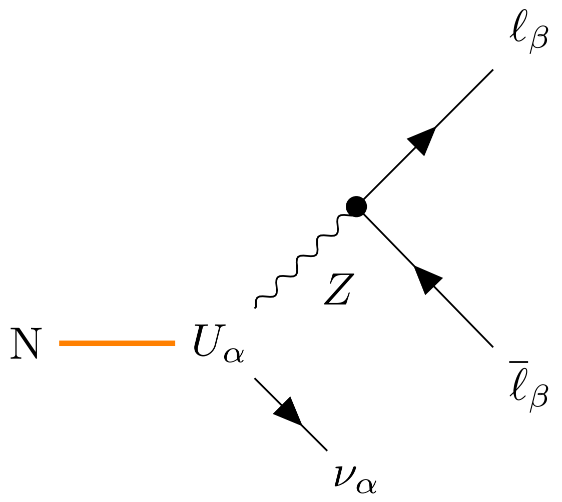
However, the interesting cases are

- electrophilic HNL to $\nu_e ee$
- muonphilic HNL to $\nu_\mu \mu\mu$

Additionally, $\nu_\alpha e\mu$ is strong for both coupling options

However, Neutrino in final state makes vertex-pointing search not appealing

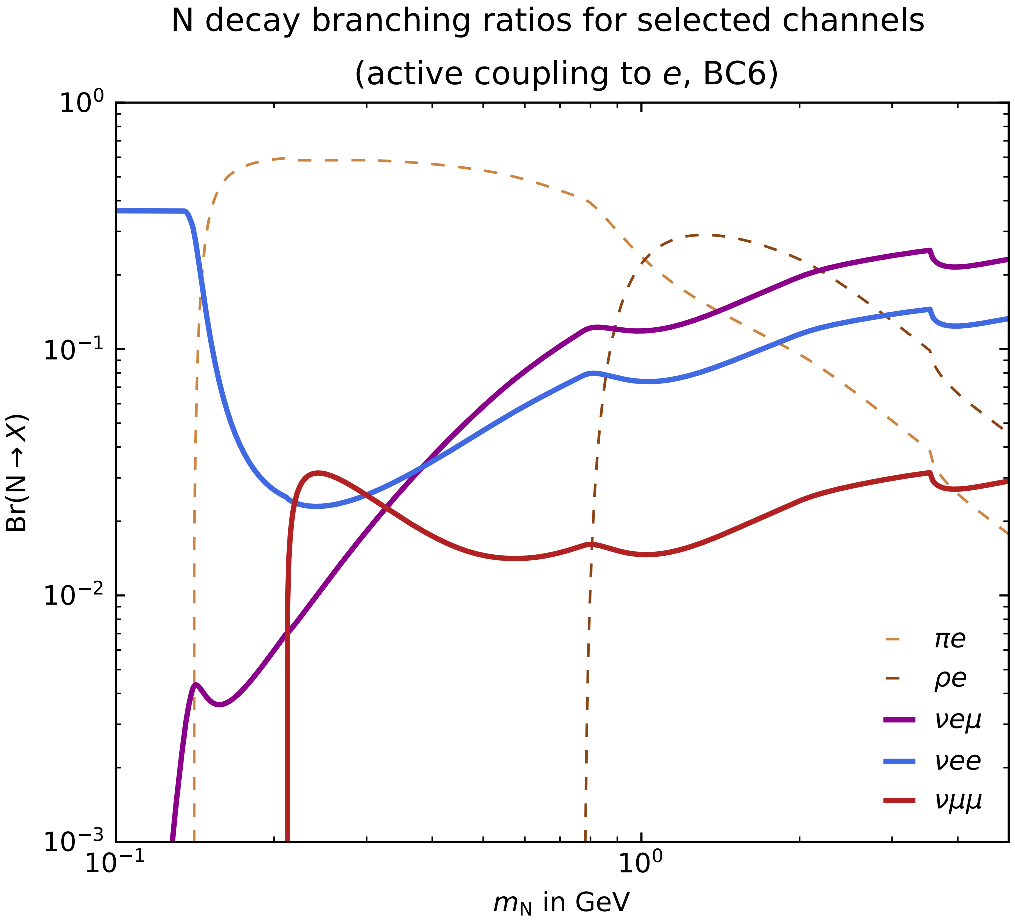


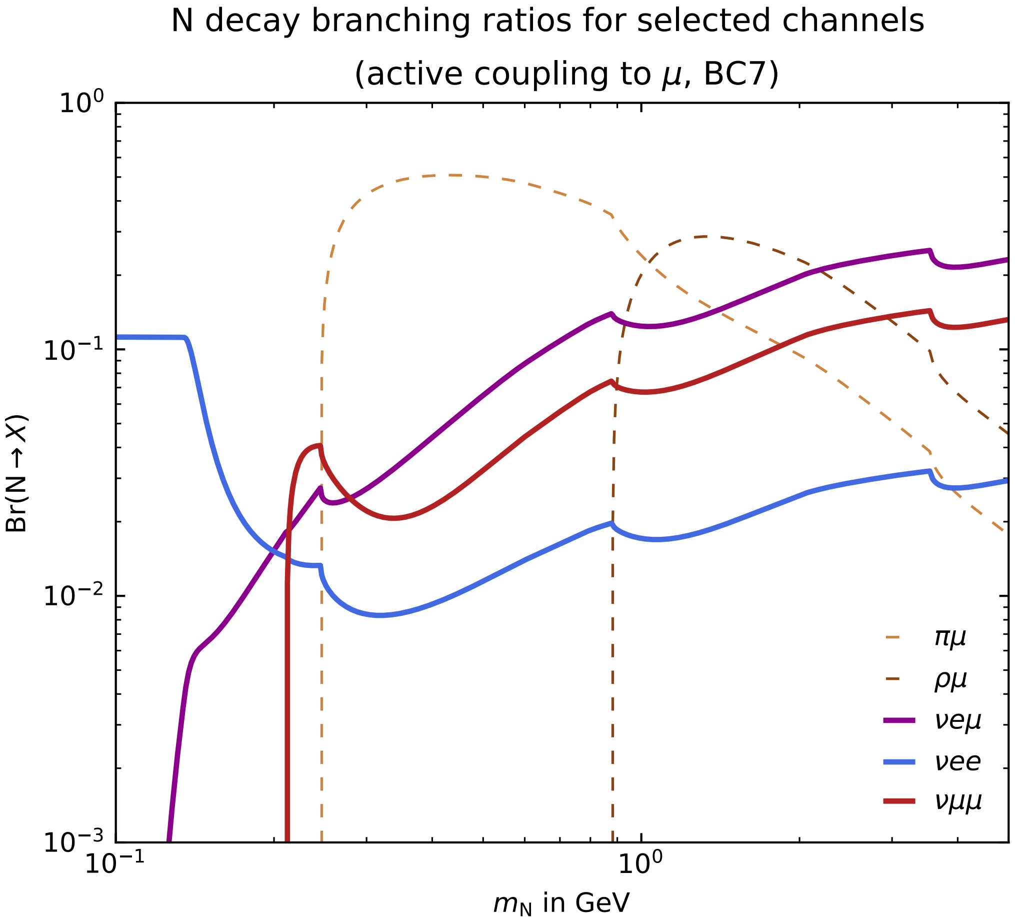


For Majorana HNL charge conjugated process is also possible

THREE BODY FINAL STATES

THE $\nu\ell\ell$ DECAY DEPENDING ON ACTIVE COUPLING





for electrophilic HNL νee more relevant than $\nu\mu\mu$

for muonphilic HNL $\nu\mu\mu$ more relevant than νee

THREE BODY FINAL STATES

THE $\nu\ell\ell$ DECAY FOR TAUPHILIC COUPLING